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***Abstract*—Hollow-core fiber (HCF) has recently emerged as a promising candidate for supporting X-haul transport with stringent latency and capacity requirements, owing to its reduced propagation delay and negligible nonlinear effects compared to standard single-mode fiber (SSMF). Despite these advantages, the implications of HCF deployment for future 6G X-haul transport under realistic fronthaul and midhaul constraints remain largely unexplored. In this work, we investigate the impact of HCF deployment on 6G X-haul over converged metro-access optical networks under joint bit error rate (BER) and latency requirements, considering functional split 7.2 as defined by 3GPP. Using an experimentally characterized digital subcarrier multiplexing (DSCM) coherent transceiver (TRx) model, we perform a route-level feasibility analysis comparing SSMF with both complete and partial replacement of metro fiber spans by HCF. While HCF provides an inherent propagation-delay advantage of up to 30% over SSMF, topology-wide evaluation shows that this translates into an average end-to-end latency reduction of approximately 9% for complete HCF deployment, together with up to 32.8% higher route feasibility compared to SSMF in the considered scenario. While complete replacement of metro spans with HCF yields the highest performance gains, selective deployment over latency and impairment critical metro segments achieves a substantial portion of these benefits with significantly reduced fiber substitution. This demonstrates that hybrid HCF deployment provides a cost-efficient and scalable design option for meeting stringent 6G X-haul transport requirements in converged metro-access networks.**

***Index Terms*—5G, 6G, X-haul, optical transport networks, hollow-core fiber (HCF), radio access networks, metro-access networks, network-as-a-service**

I. Introduction

Global mobile traffic is projected to continue its rapid growth, with a compound annual growth rate (CAGR) of 15.4% by 2030 [1]. This trend, together with emerging application domains ranging from future 6G service deployments [2] to the interconnection of AI-driven data centers [3], is expected to further stress the capacity requirements of transport networks. In this context, the evolution from 5G toward 6G also introduces unprecedented requirements on transport infrastructures in terms of latency, bandwidth, and granularity of the service. Disaggregated and open radio access network (RAN) architectures enable flexible function placement but impose stringent constraints on the underlying optical layer that connects radio units (RUs), distributed units (DUs), and central units (CUs) across the fronthaul (FH) and midhaul (MH) domains [4]. Considering functional split 7.2 defined by 3GPP [5], latency budgets below $250\,\mu s$ for FH and $1\,ms$ for MH, together with strict quality-of-service (QoS) guarantees, position metro-access optical networks as a critical enabler for 6G X-haul [6, 7]. Fig. 1 illustrates a converged metro-access network architecture supporting optical network as-a-service (ONaaS), enabled by DSCM coherent transceivers (TRxs) [8]. In converged metro-access X-haul networks, the bidirectional RU transport demand can be supported by allocating two subcarriers, consistent with split 7.2 capacity requirements (e.g., ≈22.2 Gbps per RU) [9]. However, beyond capacity

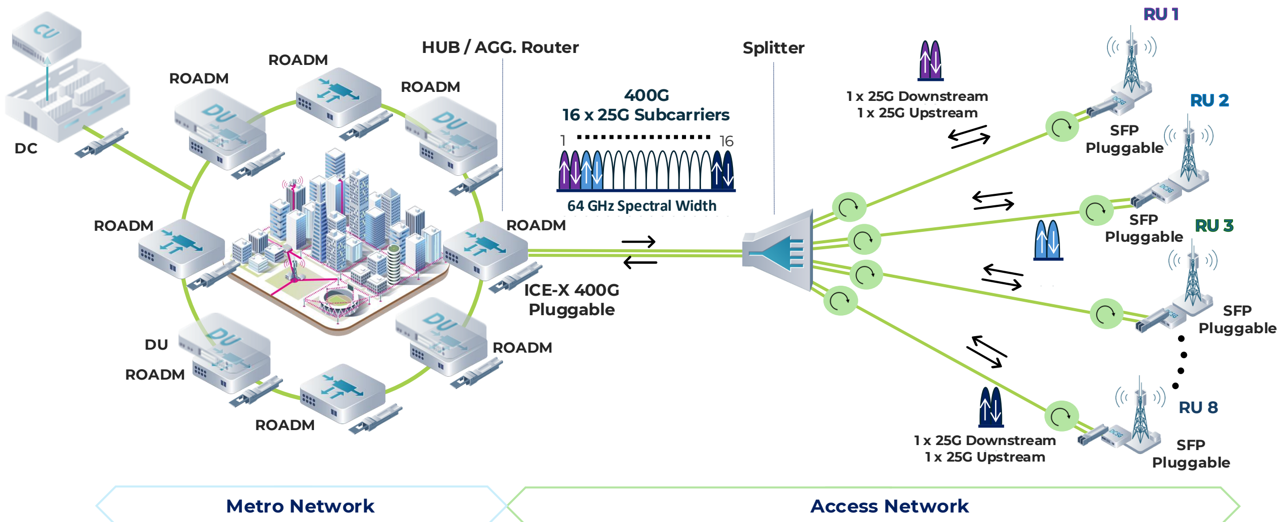

Fig. 1: Converged metro-access optical network as-a-service.

provisioning, satisfying joint BER and stringent FH/MH latency constraints over realistic metro-access routes remains the primary limiting factor for end-to-end service feasibility.

Conventional SSMF remains the dominant transmission medium in metro and access segments; however, its inherent refractive index, nonlinear impairments, and power handling limitations restrict both achievable latency and optical performance [10]. HCF, on the other hand, guides light through an air-filled core, has recently emerged as a promising alternative, offering up to 30% lower propagation delay and significantly reduced nonlinear effects [11]. State-of-the-art nested antiresonant nodeless fibers (NANFs) have demonstrated losses between [0.11 – 0.26] dB/km [12, 13], while industrial interest is accelerating with large-scale trials exceeding 10,000 km [14]. Despite these advances, replacement of SSMF with HCF remains economically prohibitive and technologically immature due to splice losses, inter-modal interference, and manufacturability concerns [15, 16].

Previous studies have examined the benefits of HCF for long-term capacity scaling [17], throughput improvement [18], and amplifier reduction [19], as well as its application within metro–DC interconnections for RAN X-haul [20], but its impact on fully converged metro-access transport for 6G X-haul remains largely unexplored. In this work, we evaluate the benefits of selective and complete HCF deployment for 6G X-haul within converged metro-access networks. A representative metropolitan network topology is analyzed under two deployment scenarios, selective and complete replacement of SSMF with HCF, considering 4 different classes of HCF with different attenuation and launch powers. This study provides novel insights into performance trade-offs and guiding hybrid integration of HCF-SSMF in future 6G transport networks.

II. Simulation Scenario

The simulation framework relies on an experimentally characterized model of a digital subcarrier multiplexing (DSCM) based pluggable TRx from which a key performance model relating Received Optical Power (ROP) and Signal-to-Noise Ratio (SNR) is derived. The abstraction of this model enables the statistical evaluation of route feasibility under BER and latency constraints in a converged metro-access network. To reduce computational complexity in the feasibility analysis, each evaluated RU-CU route was limited to a maximum of 12 hops. As shown in Fig. 2, the reference topology includes two metropolitan areas, City A and City B, each featuring metro and access segments with a cluster of access nodes. The access segment is interconnected to the metro segment through Reconfigurable Optical Add-Drop Multiplexers (ROADMs) and optical circulators, thus emulating realistic bidirectional access and dual-fiber metro operation. The structural parameters of both cities are summarized in Table I. The network architecture assumes that DUs are hosted at metro points of presence (PoPs) inside the metro network, whereas the CUs are hosted at data centers (DCs) located at nodes M31 and M32. In the hybrid deployment scenario, the metro spans marked with “=” in Fig. 2 are replaced with HCF, representing selective substitution within the SSMF-based network. The selection of metro spans for HCF replacement is based on a simplified network design assumption, where a subset of metro links forming a logical ring is envisioned to support enhanced QoS guarantees. This abstraction reflects a realistic operator strategy in which specific metro segments are provisioned with improved physical-layer characteristics to accommodate stringent X-haul requirements, without enforcing a full network-wide fiber replacement.

The end-to-end SNR combines optical and transceiver contributions, and the BER is computed assuming DP-16QAM

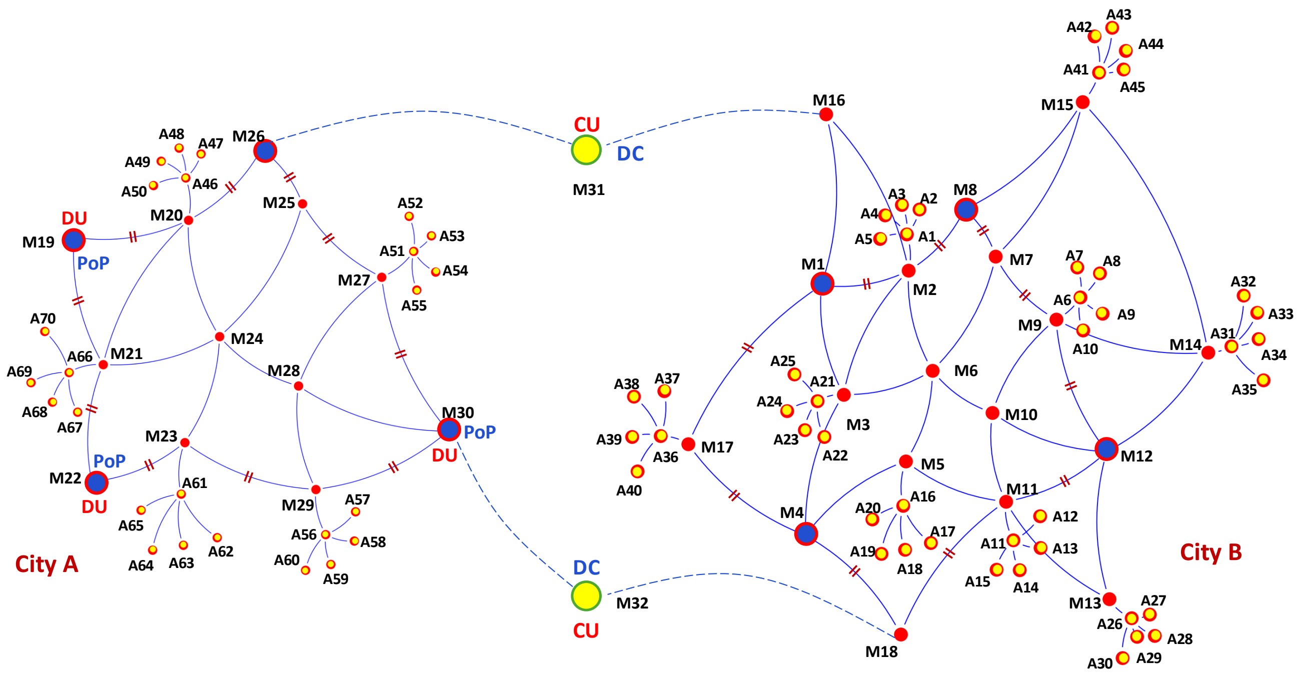

Fig. 2: Simulated converged metro-access network topology.

modulation using Eq. 1 and 2, consistent with the experimental characterization of multi-carrier TRx supporting 400 Gbps transmission following the proposed modeling methodology in [21, 22].

$$\mathrm{SNR}^{-1} = \mathrm{GSNR}^{-1} + \mathrm{SNR}_{\mathrm{TRX}}^{-1} \tag{1}$$

$$\mathrm{BER}_{16\mathrm{QAM}} = \frac{3}{8}\,\mathrm{erfc}\left(\sqrt{\frac{\mathrm{SNR}}{10}}\right) \tag{2}$$

Latency is computed from physical path lengths assuming a propagation delay, the dominant term in measuring latency, of $5\,\mu\mathrm{s/km}$ for SSMF and $3.45\,\mu\mathrm{s/km}$ for HCF, reflecting a 30% latency reduction associated with air-guided propagation [11, 12]. Four attenuation classes of HCF (0.11, 0.16, 0.21, and 0.26 dB/km) are compared with SSMF (0.25 dB/km) [23]. Owing to the extremely low nonlinear coefficient of HCF [10, 24], higher optical launch powers can be applied without incurring nonlinear penalties; therefore, analyses were performed at 0, 3, and 6 dBm for HCF [18], while SSMF was evaluated at 0 dBm. Two scenarios were investigated:

TABLE I: Topology parameters

Parameter	City A	City B
Total optical nodes	44	63
Metro nodes	12	18
Access nodes	25	45
Avg. node degree	3.42	4.06
Avg. link length [km]	6.9	7.3
Max. span [km]	10	12

(i) complete replacement of metro SSMF with HCF and (ii) selective replacement links. Route feasibility is defined when simultaneously satisfying BER, FH latency, and MH latency are met (i.e., 10^{-2}, $250\,\mu\mathrm{s}$, and $1000\,\mu\mathrm{s}$ ($1\,\mathrm{ms}$) respectively) [9, 25, 26], providing a comprehensive basis for evaluating selective HCF deployment in converged 6G X-haul networks.

III. Results and Discussions

Fig. 3 presents the distribution of route-level BER ($\log_{10}$ scale) for different HCF attenuation classes and launch powers, comparing complete and hybrid HCF deployments against the SSMF baseline. The results highlight a clear dependence of BER feasibility on both fiber attenuation and launch power for the two deployment strategies. At 0 dBm, the BER distributions of complete HCF, hybrid, and SSMF remain relatively close across most attenuation classes. In this low-power regime, performance is mainly limited by linear noise accumulation, and only the lowest-loss HCF case (0.11 dB/km) shows a noticeable improvement. The similarity between complete and hybrid deployments indicates that, at low launch power, the extent of HCF replacement has a limited impact on BER. At 3 dBm, the advantage of HCF becomes more evident. Complete HCF deployment exhibits a systematic shift toward lower BER values for attenuation classes up to 0.21 dB/km, reflecting improved tolerance to increased launch power. The hybrid deployment follows the same trend but with a smaller shift, due to the presence of residual SSMF spans that partially limit the achievable BER improvement. At 6 dBm, the performance difference is most pronounced. Complete HCF deployment maintains BER compliance over a significantly larger number of routes, while SSMF performance saturates.

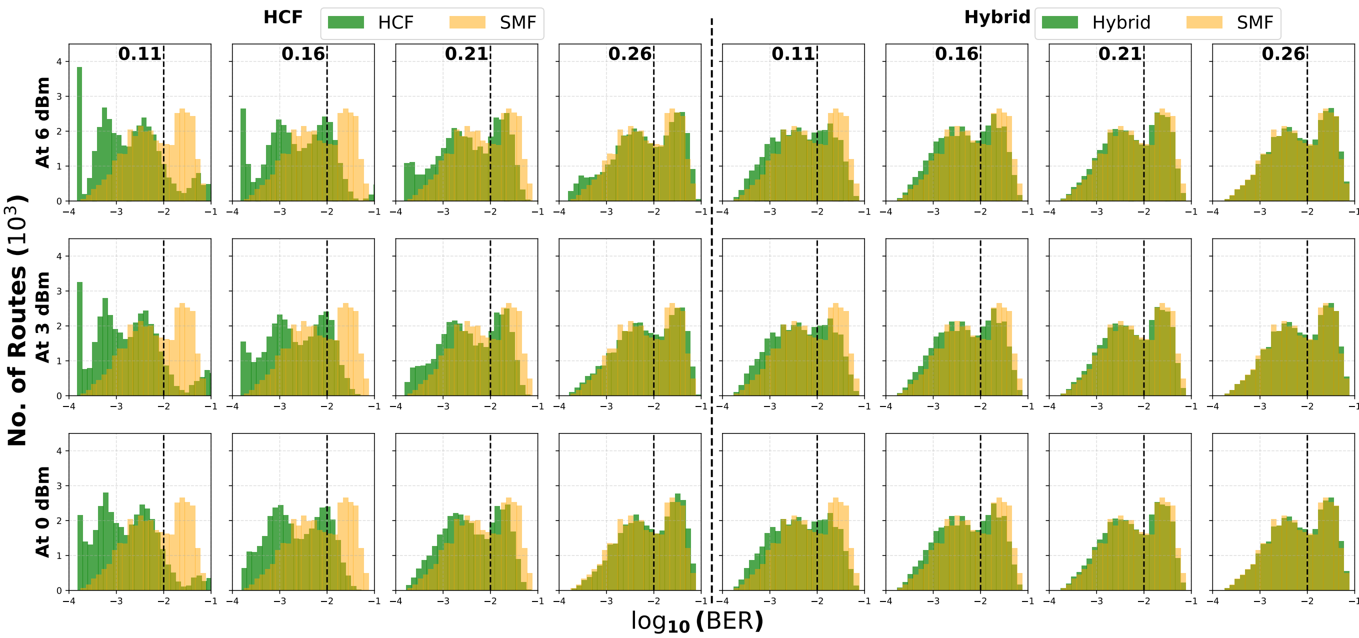

Fig. 3: BER distributions ($\log_{10}$) for HCF (left) and Hybrid (right) deployments versus SSMF across attenuation classes (0.11–0.26 dB/km) with launch powers (0, 3, and 6 dBm)

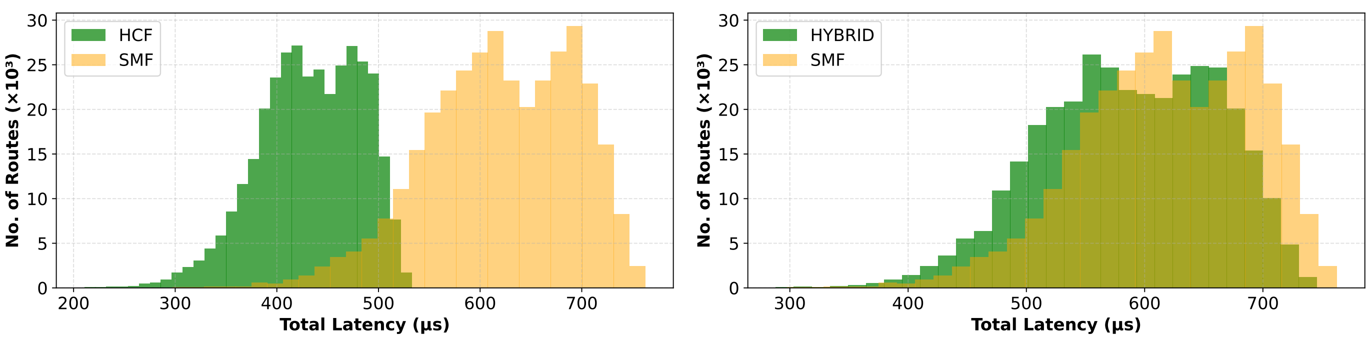

Fig. 4: Latency distributions considering HCF (left) and Hybrid (right) versus SSMF

The hybrid configuration also outperforms SSMF across all attenuation classes, although a residual gap with respect to full HCF remains, particularly for higher-loss fibers. This behavior indicates that the benefit of higher launch power is progressively reduced as the fraction of SSMF spans increases. Overall, a complete HCF deployment provides the best BER performance across all operating conditions. However, for low-loss HCF ($\leq$0.16 dB/km), the BER distributions of the hybrid and complete configurations become closely aligned, indicating that selective replacement of metro spans is able to capture most of the BER improvement while limiting the extent of fiber substitution. These results confirm that hybrid HCF deployment offers an effective compromise between BER performance and deployment complexity in converged metro-access 6G X-haul networks.

In addition to BER performance, Fig. 4 reports the total end-to-end latency distributions for HCF, hybrid, and SSMF deployments. Considering the mean latency values, SSMF exhibits an average end-to-end latency of 619.8 μs, while complete HCF deployment reduces the mean latency to 564.9 μs, corresponding to an average reduction of approximately 9%. This improvement is attributed to the lower group index of HCF, which reduces propagation delay along metro-access routes. The hybrid deployment achieves an intermediate mean latency of 606.7 μs, indicating that partial replacement of metro spans with HCF already yields a measurable latency benefit over the SSMF baseline. Although the absolute reduction is smaller than in the complete HCF case, the hybrid configuration shifts the latency distribution toward lower values and reduces the occurrence of high-latency routes. Overall, while complete HCF deployment provides the largest latency reduction, hybrid deployment captures a meaningful portion of the latency gain with limited fiber replacement. This confirms that selective integration of HCF can effectively

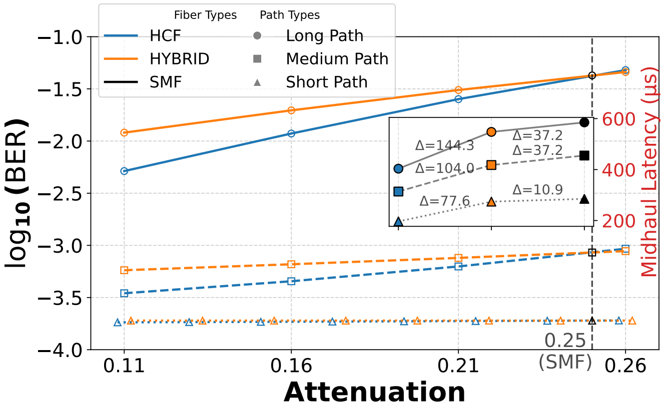

Fig. 5: BER and latency versus attenuation for different path lengths.

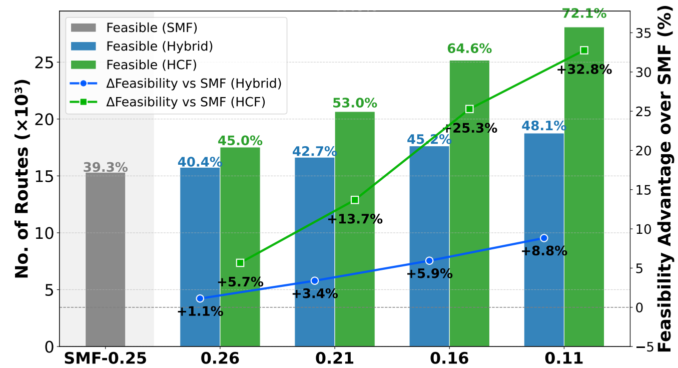

Fig. 6: Path feasibility analysis using HCF, Hybrid, and SSMF deployment scenarios.

improve latency performance while maintaining deployment flexibility in converged metro-access 6G X-haul networks.

Fig. 5 illustrates the combined impact of fiber attenuation and path length on BER and latency for the 6 dBm launch power case. The three representative paths, retrieved from the topology shown in Fig. 2, used for this analysis are: short (A25–A21–M3–M4–M18–M32, DU at M4), medium (A23–A21–M3–M1–M2–M6–M10–M12–M11–M18–M32, DU at M1), and long (A42–A41–M15–M7–M9–M12–M11–M5–M4–M17–M1–M16–M31, DU at M12). The results show a consistent BER improvement for both complete and hybrid HCF deployments compared to SSMF across all path types. For short routes, dominated by access segments, the BER remains largely insensitive to attenuation and fiber type, as accumulated impairments are limited. In contrast, for medium and long routes traversing multiple metro spans, attenuation and noise accumulation become dominant, leading to a pronounced separation between SSMF and HCF-based solutions. For long paths, HCF provides up to one order of magnitude BER improvement at low attenuation (0.11 dB/km), while the advantage progressively reduces as attenuation increases, confirming that fiber loss ultimately bounds performance even in the absence of nonlinear penalties. The hybrid deployment closely follows the HCF trend for medium and long paths, indicating that replacing only the dominant metro spans is sufficient to capture most of the BER benefit. The inset further reports the corresponding end-to-end latency, showing that absolute latency savings are largest for long paths, where propagation delay is dominated by metro segments. Moving from SSMF to hybrid and full HCF deployment reduces latency by approximately 144 µs, 104 µs, and ≈78 µs for long, medium, and short paths, respectively. These results reinforce that hybrid deployment delivers substantial performance improvement with limited fiber replacement, making it an effective compromise between optical quality, latency reduction, and practical deployability for 6G X-haul.

Fig. 6 compares the overall route feasibility across different fiber configurations. The results reveal a steady increase in the percentage of feasible routes as the HCF attenuation decreases, reaching 72.1% for complete deployment and 48.1% for hybrid deployment at 0.11 dB/km, compared to 39.3% for the SSMF baseline. Even at higher attenuation levels (0.26 dB/km), both hybrid and complete HCF scenarios already outperform SSMF due to the absence of nonlinear limitations. The relative feasibility improvement further highlights the effectiveness of selective deployment. Complete HCF replacement provides feasibility gains up to 32.8% over SSMF, while the hybrid approach achieves gains up to 8.8% with substantially reduced fiber replacement. These improvements are driven by the combined effect of enhanced BER performance and reduced propagation latency, which jointly enable a larger set of routes to satisfy fronthaul and midhaul constraints. From a network design perspective, these results indicate that feasibility is primarily limited by a subset of long, impairment-critical routes. Targeting these routes through selective HCF deployment leads to a significant increase in service acceptance, demonstrating that hybrid HCF constitutes a scalable and deployment-efficient solution for 6G X-haul transport in converged metro-access networks.

IV. Conclusion

This work has evaluated the impact of HCF deployment on 6G X-haul transport within converged metro-access optical networks using experimentally validated transceiver-based modeling. Route feasibility has been assessed under combined BER and latency constraints across multiple fiber attenuation classes and launch power levels, comparing SSMF with both complete and selective HCF deployment strategies. While HCF offers an inherent propagation-delay advantage of up to 30% over SSMF, the topology-wide evaluation shows a measurable reduction in end-to-end latency and a substantial increase in the number of routes satisfying fronthaul and midhaul requirements. While complete replacement of SSMF with HCF yields the highest feasibility gains, selective deployment over selected metro spans supporting stringent X-haul requirements achieves reasonable performance improvements with far lower infrastructure modification. Overall, the presented analysis demonstrates that hybrid HCF deployment constitutes a practical and scalable solution for supporting stringent 6G X-haul requirements, providing a favorable trade-off between performance gains and deployment cost. These results support the adoption of selective HCF integration as an effective design option for future metro-access transport networks enabling disaggregated and virtualized RAN architectures.

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